FOVEAL ADAPTATION TO COLOR[1]

By Hubert Sheppard

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Introduction

The primary aim of this study is to describe the course of foveal adaptation to color. We have also obtained records of the times of adaptation, and have attempted to show their variation with variations of intensity and chroma; but our main purpose throughout the experiment has been to secure introspective reports of the attributive changes which occur while the fovea or macula lutea is under stimulation by a color, from the moment of exhibition until the color has disappeared or until there is no further alteration of hue or tint or chroma. The peripheral retina is discussed only in so far as its discussion bears upon adaptation at the fovea.

Wherever possible, all earlier experiments which seemed to relate, directly or indirectly, to our problem were repeated, and their results tested, before our own technique was finally decided upon. Very little work has been done, however, that bears directly upon foveal adaptation considered as a mode of experience. Adaptation in general depends (1) upon wave-length, wave-form, and wave-amplitude of light, and (2) upon the time during which the light-waves affect the eye. Hence the problem may be approached from the side of light-dark adaptation, of color adaptation, or of negative after-image. Previous investigators have studied the first and third

[1] From the Psychological Laboratory of Cornell University.

of these topics rather than the experienced course of color adaptation.

The term *adaptation*, as applied to visual experiences, was first used by Aubert, to denote "the accommodation of the eye to light-intensities."[2] Nowhere in his writings does Aubert connect this term with color-changes, for which he uses the term 'fatigue.' In his paper on fatigue and retinal after-image,[3] as elsewhere, he argues that there is a close analogy of function between the fovea and the peripheral retina. Colored objects, he says, appear colorless in both direct and indirect vision, if the stimulus is sufficiently long continued. He is, therefore, familiar with complete adaptation, but includes it under the term 'fatigue.'

Exner, working under the direction of Helmholtz, made the first systematic study of adaptation (fatigue) to color-stimulation.[4] In an experiment in which he describes the course of the after-image, he finds that three parts of the spectrum are much less altered in appearance by 'fatigue' than other parts, namely, *R* from the end of the spectrum to a point between the lines C and D, *G* between E and b, and *B* near G. He notes also that, if the after-image of a color is projected upon another color of the same hue, this second color appears much less saturated.[5]

Von Kries investigated the problem of adaptation from both the physical and the psychological points of view. He found that "with long fixation, a color loses in brightness as well as in saturation."[6] suffer no change in hue, while the other colors change in the direction of *Y* or *B* from *G*.

Hess made a study of the tone-changes of spectral colors when the retina was fatigued with homogeneous light.[7] He observed that all colors possess either a *Y* or a *B* valence. That is, all colors, from near a pure *R* to a pure *Y*, or near a pure *G* to a pure *Y*, will change under adaptation towards *Y*; and all colors from near a pure *R* to a pure *B*, or near a pure *G* to a pure *B*, will change towards *B*. Further, during the process of adaptation the stimulus-color always becomes less and less saturated, until it disappears; the complement of the stimulus-color always remains unchanged in hue; and the appearance of a spectral color after adaptation corresponds in general to a mixture of that color with its complement.

Burch was able to produce temporary color-blindness by means of general adaptation at any intensity.[8] In an article entitled "On the Production of Artificial Colour-blindness to Successive Contrast" he describes the process of adaptation as complete for *R, G, B* and *V*. In another experiment he was able to get complete adaptation in 3 min. when the intensity of the stimulating light was bright moonlight. His method for very high intensities was as follows: The eye of an

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[2] H. Aubert, *Physiol. d. Netzhaut,* 1865, 39 ff.

[3] Moleschott's *Untersuch.,* IV, 1858, 220 ff.

[4] J. Aitken, *Roy. Scot. Soc. of Arts, Proc.* 1871-2, and E. Hunt, *Colour Vision,* Glasgow, 1892, made similar studies of adaptation. A detailed account of their method and procedure is given later by Burch.

[5] S. Exner, 'Ueber einige neue subjective Gesichtserscheinungen,' *Arch. f. Physiol.,* I, 1868, 375-394.

[6] Nagel's *Handb. d. Physiol. d. Mensch.,* III, 1905, 213-220.
Further, *Y* of a wave-length of 560 $\mu\mu$, *G* of 500 $\mu\mu$, and *B* of 460 $\mu\mu$

[7] C. Hess, *Arch. f. Ophth.,* 1890, XXXVI, Abtl. 1, 1 ff.

[8] G. J. Burch, *Phil. Trans.,* 191 B, 1899, 1-135. *Roy. Soc. Proc.,* 66, 208 ff, 216-219.

observer was exposed to bright sunlight, which had been focussed by a burning-glass through a colored screen. After the eye had been subjected to this intense light until all sensation of the particular color was lost, the observer proved to be temporarily color-blind to the color used in stimulation. Further, four parts of the spectrum, *R* from A to B, *G* in the neighborhood of E, *B* about half-way between F and G, and *V* at and beyond H, showed marked fatigue-effects, differing in degree but not in kind. All direct sensation of the stimulus-color was temporarily lost: *R* for 10 min., *G* for a still longer period, while the recovery from *V*-blindness might require a couple of hours. Whenever the eye is completely fatigued to any color, that color is absent from the spectrum, whatever the fatiguing intensity may have been. The observer is, in fact, color-blind for the particular color. After fatiguing the eye with three of the four colors, Burch found that only one color remained.[9]

Troland has unpublished data from which he is able to determine a theoretical course for the process of adaptation in all the adapting sense departments. Retinal adaptation follows the same general course as that of the other adapting organs.[10] The rate of the process is greater in the beginning, with a decrease rapid at first, then more gradual, until it finally reaches a level at which it is constant.[11] Troland finds also "that, at least for stimuli of fairly high intensity, adaptation does not proceed to a point at which the resultant sensation reduces to a neutral gray."[12]

In sum, then, Exner, von Kries, and Hess come to almost exact agreement with regard to the gross results of adaptation to color. (1) The 'primary' colors, *Y* 550-574$\mu\mu$, *G* 495-520 $\mu\mu$, *B* 435-471 $\mu\mu$, do not change in hue under the process of adaptation. Hess finds a psychological *R* outside of the solar spectrum which also does not change. All other colors change either towards *Y* or towards *B*. (2) A color, after adaptation, corresponds in general to a mixture of this color with its complement.

As regards adaptation to color at high intensity, there is difference of opinion. Burch gets complete general adaptation with any intensity which produces temporary color-blindness to the stimulus-color. Troland, on the other hand, finds that color-adaptation at high intensity does not reduce the color to a neutral gray.

Experimental: Plan of the Experiment

The present experimental work upon foveal adaptation to color was begun in October, 1918, and ended in September, 1919. The observers were Dr. C. W. Bock (B), Mr. H. Sheppard (Sh) and Mr. M. J. Zigler (Z), instructors in psychology, and Mr. H. Liddell (L), Miss A. K Sullivan (S), and Miss M. Finck (F), graduate students in the department. L, S and Z were given several weeks' training before any data were taken for our records; F was relatively unpractised.

[9] A. W. Porter and F W. Edridge-Green, *Proc. Roy. Soc.*, 85 B, 1912, 435 ff, find somewhat different results for *B* and *G;* but Burch, *Proc. Roy. Soc.*, 86 B, 1912-13, 117-18, argues that their work was not carefully done, and that their results are not strictly reliable.

[10] L. T. Troland, *Am. J. Psych.*, 25, 521 ff.

[11] *Ibid.*, 508.

[12] *Ibid.*, 520.

Our object, as has been stated above, was to describe the course of foveal adaptation to color under as many different conditions as possible. We do not attempt a theory, nor do we draw any theoretical conclusion whatever.[13] We aim only at a qualitative study of the experienced course of adaptation, with secondary reference to the times of adaptation for the different colors used.

The experiment as a whole comprises three parts. In Part I. we examine general adaptation to a surface color in direct sunlight. Here the experienced course of adaptation is described in its various stages. In this preliminary experiment we also take account of foveal adaptation in a general and tentative way. In Part II. we work with surface-colors, and the process of adaptation takes place under certain controlled conditions. These conditions greatly reduced eye movement, and kept the illumination constant. Here we describe the experienced course of foveal adaptation to 9 different colors, *R, O, Y, YG, G, BG, B, V,* and *C*. In addition we consider the effect of chroma upon adaptation. In Part III. pure spectral colors are used with various intensities of illumination. Here we describe the experienced course of foveal adaptation, and note in what respect this process differs from the course of adaptation when a surface-color is used. Difference of chroma is also considered. Two colors, differing in hue, are matched for chroma, and the process and time of adaptation are recorded in each case. We also give the results of some experiments made with high intensities of stimulus.

Part I.: Preliminary Experiment

General Adaptation in Direct Sunlight

We are here concerned to determine the course of general adaptation when a surface-color, illuminated by direct sunlight, stimulates the entire retina. In former experiments peripheral adaptation to color has been found to be more rapid than foveal.[14] Our main problem throughout the preliminary experiment was the study of the course of adaptation, by introspective observation, as the process travelled over the retina from periphery to fovea. If there is a rapid fading-out of a color under peripheral stimulation, as is indicated in the literature, it ought to be possible to observe this change in its progress towards the central retina.

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[13] Papers on 'An Experimental Treatment and Discussion of the Theory of Adaptation and Color Vision' as well as 'The Early Development of Color Vision' are now under consideration and will follow shortly.

[14] J. W. Baird, *Color Sensitivity of the Peripheral Retina*, 1905, 53-74.

Procedure.—A drawing-board of 28 x 36 in. was fastened in a window on the west side of the optics room. The board served as a table upon which to place the stimulus-color. The following papers were selected for stimuli in the preliminary tests:

Color	Brightness Value		Match to a Gray	Brightness Value of Match	
	Black	White		Black	White
R	288°	72°	211°	88°	272°
BG	206	154	149		
Y	144	216	170	154	106
B	263	97	190		
GY	162	198	125	112	248
V	285	75	235		
C	259	101	208		
G	250	110	132	97	263
B					
O	216	144	92		
G			120	112	248
B			148		

A sheet of colored paper, 19 x 24 in., was spread upon the table. In the center of the sheet was a very small light dot for a fixation-point. *O* sat facing the stimulus with one elbow resting upon the table and the chin in the palm of the hand. This position brought the eye within about 25 cm. of the fixation point, and was found to be convenient for fixation in monocular vision. All the experimental work for this part of the experiment was done during the months of July and August, from 2 to 4:30 o'clock in the afternoon. We were careful to select days when the sky was free from clouds or haze.[15]

The instruction to *O* was to report all change in color sensitivity, from the time the eye first fixated the stimulus until the color either faded out to a gray, showing no trace of color, or reached a stage where no further change in hue, tint,

[15] It is very difficult to get complete adaptation to *R, BG, B, C* and *V* in a reasonable length of time unless the sun is shining brightly. The sky must be free from clouds or haze, or the times of adaptation will vary considerably.

or chroma was perceptible. *O* was asked to give a running report of all sensory change, and in as much detail as possible.

Results.—The results are given in summary for the different observers and stimuli.

Observer B. Stimulus *Y*.—A gray film soon appeared in front of the stimulus-color. This film came in from the periphery. There was a slow change in chroma until the color faded out to a white or very light gray. A small area surrounding the fixation-point persisted longer than the other parts of the field. The change was slow at first, then more rapid towards the last.

Stimulus *BG*.—The outer edge began to pale rapidly at first. This paling extended inward towards the center. The center remained richer in chroma than the outer edge for some time. Finally the surface evened up into a gray field.

Stimulus *B*.—There was no change in hue. The haze appeared over the surface from the outside, although very slowly as compared with some of the other colors. The color persisted for a considerable time around the fixation point. In the process of fading out there were many bluish spots scattered about among white filmy spots. These spots would even up into a white or light gray surface.

Stimulus *R*.—While the color was fading out from the periphery, certain portions did not appear uniformly colored; little filmy red dots were scattered about over the surface. Finally the red spots paled out to gray, and then evened up over the whole surface. The color around the fixation-point remained for some time as a dirty brown color. The final gray surface was very dark.

Stimulus *V*.—There was a rough cloudy surface over the color for a considerable time. The color began to pale out from the outer edge, and the change traveled towards the center. The roughness always smoothed out into a gray film of a thick texture. It is very difficult to tell just when adaptation is complete.

Stimulus *O*.—It faded into a beautiful light yellow, beginning on the outer edge and gradually decreasing towards the fixation-point. From the *Y* it went into a gray which was somewhat darker than the *O*. The steps were perceptible though gradual. All changes were from the periphery towards the center.

Stimulus *C*.—Almost immediately the surface began to grow white in the outer portion of the field. This white gradually approached the center. The final stage was a lustrous silvery gray.

Stimulus *G*.—There was a slow change in hue from *G* through *Y*. The *Y* finally changed into a very light gray, very much lighter than the stimulus-color.

Stimulus *GY*.—The green faded out of the periphery very quickly. This process always took place before the *Y* began to go. The *Y* then changed into a very light gray. The surface of the stimulus-field at times had a rough, uneven appearance. This gradually changed into an even surface without any color.

Observer Sh. Stimulus *Y*.—Almost immediately the color began to grow lighter and the chroma poorer. There was no change in hue. As soon as the color began to fade a filmy surface appeared over the surface of the color. The fading out process always came from without towards the fixation-point. The periphery became white some time before the fixation-point. The final stage was an almost white surface.

Stimulus *BG*.—There was a gradual, though rapid decrease in saturation from the beginning. Also there appeared a very rough, uneven surface about the fixation-point, which was much more satu-

rated than the rest of the field. This area gradually evened up into a gray. The hue changed slightly to *B*.

Stimulus *B*.— The blue faded out very slowly from the periphery to the center. At all times the hue appeared to shine through a white filmy surface which formed over the color. This effect persisted to the end.[16] The complete stage of adaptation was a very pretty whitish gray, like an after-image of a velvet-black surface. There was no hue-change whatever that could be observed. The entire process was a slow fading away of the color into a filmy surface. Two cases of staring blindness occurred during this series of observations.

Stimulus *R*.— The red is unlike any other color in adapting out to a gray. It passes through different stages of hue-change from the first. Almost immediately it passes over into a red-orange, then to an orange of poor chroma, and finally into a dirty, dingy brown, which is very persistent. This brown finally goes into a poor gray, then to a good gray surface.

Stimulus *V*.— Violet is the most stubborn of all the pigment-colors to a complete adaptation in sunlight. There is a feeling of uncertainty as to the judgment, because the violet is almost of the same brightness as the gray surface which persists when adaptation is complete. (The two are so near alike that it is often difficult for *O* to decide when the final stage is reached.) There is a rough cloudy surface at first, which gradually smooths down with time. Two changes in hue always take place. At first there is a tendency for the red to persist; this presently adapts out, and leaves a bluish-violet surface of very poor chroma.

Stimulus *O*.— Orange adapts out very much like red from the second stage of the red, except that the orange is richer in chroma than the red at this stage. When the color reaches the brown stage, it is almost exactly like the same stage in the red, except that the orange is brighter than the red. One effect of staring-blindness was observed, which lasted for three or four seconds.

Stimulus *C*.— Almost immediately the surface began to take on a bright lustrous appearance. This effect gradually thickened, until the whole surface was of a beautiful silver lustre. The hue changed somewhat to blue, thus causing the surface to become darker.

Stimulus *G*.— For the first few seconds the color did not appear to change. Suddenly there is a change, the yellow appears and the green seems to weaken. From this point there is a rapid fading away. The yellow appears to go out first; the green, now much less saturated, fades out into a beautiful gray surface which is very smooth in texture. Two cases of staring blindness were observed.

Stimulus *GY*.— The color is stubborn at first; the green suddenly goes out; and then there is a gradual, though rapid, fading away of the yellow to a beautiful gray surface. After the green passes away, the process of adaptation is very much like that of the yellow. The final stage, the gray surface, is similar to the same stage in the yellow adaptation.

Observer Z. Stimulus *Y*.— The color began to fade in the periphery almost immediately; this caused the center to appear much lighter, and richer in chroma. The small center persisted for some time, although slowly fading all the time. Finally the whole surface of the stimulus-color became a uniform gray

[16] To get the effect of the soft white surface, when adaptation is complete, a Hering blue must be used. A paper that has a glossy surface is very difficult to observe for this length of time.

Stimulus *BG.*— There was no apparent change in hue. A thin filmy mist came in from the edge of the paper, which caused all color to disappear from the periphery. This colorless effect gradually went towards the center, until the whole color disappeared.

Stimulus *B.*— No hue-change. The light or white foggy mist approached the center from the periphery until the whole surface was a very poor *B*, almost gray. This state persisted for some seconds. Finally all color faded away, leaving only a gray field.

Stimulus *R.*— There was always a decided hue-change. It went first to a very poor yellowish *O*, then to a dirty yellow gray. This persisted for some seconds. The final stage is a peculiar gray. It appears to be a little darker than the stimulus-color.

Stimulus *V.*— There was a slight hue-change to *B*. The decrease in chroma was marked at first. However, the final state is difficult to judge, since the final gray and the *V*, very poor in chroma, are much alike.

Stimulus *O.*— There was a change in hue to *Y*, poor in chroma. This change began in the periphery, and traveled towards the center. Finally the center went out, exactly like the *Y*.

Stimulus *C.*— This is a very stubborn color. It appears to be uneven in surface during the adaptation-process. It changes from periphery to center, but not so markedly as the other colors. The rough uneven surface seems to smooth down into the dark gray film as it thickens over the surface. There is a hue-change, but it is difficult to observe in its course. It would appear to change to *B*, although this can not be observed clearly.

Stimulus *G.*— Very slow change to *Y*. This change only comes about when the color has lost nearly all chroma. The film thickens from the periphery towards the center. This gradually conceals all color. The resulting gray surface appears to be a little lighter than the stimulus-color.

Stimulus *GY.*— The periphery began to fade very quickly. For several seconds this part of the field looked like wool, while in the center of the field there was a *YG* of very good chroma. Finally the center began to fade out, rather suddenly, to a good gray surface. The hue changed to *Y*, although the final stage came when the color was very low in chroma.

Observer S. Stimulus *Y.*— The film came over the surface from the periphery in 20 seconds. There was no apparent change in hue. The final stage was a colorless paper.

Stimulus *BG.*—No change in hue. The surface began to fade out from the periphery, all the time going towards the center.

Stimulus *B.*— Same process as the *BG*. The final gray was somewhat lighter than the stimulus-color.

Stimulus *R.*— There was decided hue-change as the color began to grow less saturated by the gray film which came in from the periphery to the center. The color went through a poor *O* to a very weak muddy *Y*. This last stage persisted for some seconds.

Stimulus *V.*— This is a very stubborn color. It is difficult to decide when all the color has faded out. The film began to appear on the periphery very quickly, moving to the center. The final stage appears to be of about the same brightness as the stimulus-color. There is a hue-change to *B*, although it is very difficult to judge.

Stimulus *O.*—The film began in the periphery. For a little, this seemed to hang on the outer part of the color. Finally it moved over

the center. At this time the hue changed to a very poor *Y*. Then the process was the same as *Y* in the last stage.

Stimulus *C*.— The color made some change in hue, but it was so slow and gradual that it was difficult to judge. There was a peculiar uneven surface during the course of adaptation. The cloud appeared from the periphery, moving to the center. This gradually weakened the chroma.

Stimulus *G*.— A hue-change to yellow in the final stage. The chroma gradually grew less, the center remaining longer.

Stmulus *GY*.— Same as *G*, except that the change to *Y* was more marked.

The first part of the accompanying table shows the adaptation-times under the conditions described. The second part shows times obtained, still in direct sunlight, when a disc, composed as indicated in the table, was viewed against a large grey background. Observation in these circumstances was difficult, owing to the lack of a fixation-point.

ADAPTATION TIMES, IN SECONDS.

AVERAGE OF FIVE OBSERVATIONS

Obs.	Sh		B		Z		S		
Color	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av. of Av.
R	198.2	6.5	192.6	10.5	190.8	9.4	194.8	5.0	194.1
O	89.6	3.9	89.4	6.9	91.8	5.4	93.8	1.4	91.1
Y	45.6	3.9	39.2	3.8	43.6	6.3	55.0	1.2	45.9
YG	49.2	7.1	53.2	5.8	50.4	6.5	52.4	7.4	51.3
G	52.0	6.8	54.6	9.5	49.6	2.9	56.6	3.5	50.6
BG	126.6	5.6	109.4	11.9	115.2	9.3	128.0	4.0	119.8
B	247.6	4.7	220.2	12.9	201.8	8.6	211.4	4.7	220.0
V	200.0	8.4	201.4	4.7	201.8	1.7	234.0	10.8	209.3
C	102.0	8.4	100.0	10.0	108.0	1.6	111.0	4.8	105.2

180° OF COLOR + 180° OF BLACK AND WHITE (BRIGHTNESS-VALUE)

R	93.8	7.0			104.0	8.6	96.8	12.6	98.2
O	42.0	5.2			45.5	3.2	45.2	4.2	44.2
Y	21.0	2.0			27.0	5.4	22.2	1.8	23.4
YG	25.4	4.7			29.0	2.1	26.0	4.8	26.8
G	26.0	7.8			23.5	6.6	21.6	4.3	23.7
BG	57.0	4.8			50.3	3.4	56.0	6.4	54.4
B	118.0	13.6			122.0	2.6	123.8	7.0	121.3
V	108.0	6.4			98.6	4.8	112.8	7.1	106.5
C	53.4	7.1			44.3	2.4	52.0	6.0	49.9

FOVEAL ADAPTATION AT MEDIUM INTENSITY

PRELIMINARY SERIES

We next sought to determine the experienced course of adaptation to color, at medium intensity, when only the fovea was stimulated by the color.

For stimuli, a circular disc, 100 cm. in diameter, was cut from each one of the 9 colors shown in the preliminary experiment. Every disc was mounted upon a gray background of 24 x 30 in. The background was free from any trace of color, and had a brightness-value of 140° white and 220° black. A frame on a table held the stimulus-card upright. The stimulus was placed at a distance of 225 cm. from the eye of the observer; the image of the stimulus-color fell within the macula.

The experimental work was done in a large light optics-room. Light window-shades were drawn over the windows, so that the room was mildly illuminated with a soft white light. The instructions to *O* were the same as in the preliminary experiment.

The quantitative results (times in sec.) are set forth in the following table. The averages are of 5 observations.

Obs.	Sh.		S.	
Color	Av.	M.V.	Av.	M.V.
R	137	7.5	178	8.1
O	140	6.5	140	8.4
Y	100	4.5	105	4.2
YG	88	4.5	95	7.0
G	80	5.5	110	6.2
BG	100	3.2	98	3.1
B	118	4.5	109	3.2
V	201	10.5	199	7.0
C	175	7.2	178	8.0

The reports of the observers may be summarized as follows:

R. The color began to lose in chroma very quickly. The outer edge of the circle paled out first, the paling gradually approaching the center. There was a little hue-change; the *R* faded slightly towards a very poor *O*. The resultant gray was a little lighter than the stimulus-color.

O. A thin gray film gradually thickened over the surface of the color. This caused the chroma to become poorer with the progress of adaptation. The hue changed slightly towards a *Y*, very poor in chroma.

Y. The hue faded away under the gray film until no color was perceptible. There was no hue-change.

YG. There was a hue-change to *Y*, very poor in chroma. The final stage was somewhat darker than the color.

G. The hue changed to *Y*, very poor in chroma. The gray film

very quickly obscured the surface of the color, only a greenish gray remained for some time at the last stage of adaptation. Slightly darker than the stimulus-color.

BG. There was no perceptible hue-change, only a fading out to a very pretty gray. The film began to come in from the edge of the disc, gradually approaching the center of the color. The gray field was a little darker than the stimulus-color.

V. The hue changed to *R* and then to *B*. The resultant gray was lighter than the stimulus-color.

B. There was no perceptible hue-change in this color. In every respect it faded out like the *BG*.

C. Gradually faded out to a *B*, very poor in chroma. This state persisted for some time. Then the field was almost of the same brightness as the stimulus-color.

It soon became evident that this experimental arrangement was unsatisfactory. The observers complained of eye-movement in almost every observation; and the difference in illumination from day to day influenced the adaptation-time considerably. Further, there is a marked difference between the adaptation-times of the two observers for certain colors, especially *R* and *G*. It was therefore necessary to secure better conditions of observation.

Part II.: Foveal Adaptation at Medium Intensity Controlled Series

Procedure.—The experimental work was done in a dark room. The apparatus and stimuli were those described in our account of the preliminary series. The illumination was produced by three 75-watt, 110-volt, Edison-Mazda daylight bulbs; it was equal to 212.4 c. p. at a distance of 2.5 m. from the stimulus-color and a distance of 1 m. above and a little in front of *O*. The current was supplied by a D. C. motor in the university service.

In order to avoid eye-movement, as far as possible, the following precautions were taken. (1) A time-recording apparatus was constructed, to register accurately the time of every change in visual sensation. This made it needless for *O* to speak during an observation. The recording apparatus consisted, first, of a kymograph, set to revolve once in 3 min. A double electrical contact-marker worked over the smoked drum. To one marker was attached in circuit a large seconds-pendulum, while the other marker was in circuit with a telegraph-key operated by *O* in reporting the sensory changes. (2) A comfortable head-rest was fastened to the table in front of the stimulus-frame. With this arrangement, *O* could hold the head in a constant position during an observation.

O adjusted the head-rest, covered one eye with a black velvet eye-shield, and made ready to fixate the stimulus when the

light was turned on. The instructions were as follows: "When the light is turned on, fixate the center of the colored disc, and hold it if possible without moving the eye. If the eye does shift from its fixation, bring it back to position as quickly as possible. When the light is turned on and you have fixated, press the telegraph-key five times in rapid succession. Every time the eye moves in any way during fixation, press the key once. For every color-change of any kind, press the key twice. When the color fades out, or when it reaches a point where it shows no further change, press the key again five times. You will be asked to give an introspective report of these changes at the end of every observation."

Results.—The results are given in summary for the different observers and stimuli.

Observer S. Stimulus *Y.*— An after-image came very quickly. The mist appeared from the outside, causing the color to become less saturated and much lighter. As the mist grew thicker, there was a tendency for it to fuse in the border before the center became solid; thus the center was the last part to disappear. The cloud was much lighter than the background.

Stimulus *BG.*— The after-image was noticed very quickly. Soon the cloud gathered over the surface of the color like a fog or mist. This caused the color to be much less saturated. For a little while I could see the color through the fog as if it were behind the mist. The cloud which covered the color was darker than the stimulus-color.

Stimulus *B.*— A soft white film began to form over the surface; at about the same time I observed the after-image; in fact, the after-image and the fog could be clearly recognized as one. The after-image was merely superimposed over the color, and appeared to stand out from the color. Where this haze fell on the outside edge of the stimulus-color and on the bordering background, it took on the nature of the after-image; where it was on the stimulus-color it was a beautiful white fog or mist. As this mist or fog gradually grew thicker, the color slowly lost in richness of chroma without any hue-change. The resulting gray was of the same shade as the background.

Stimulus *R.* The gray film was peculiar in this color. It came in from the outside. The color appeared very dark through it. The mist was not smooth, but rough, very much like hazy clouds on a summer afternoon. It never had a smooth texture, like the blue, yellow or orange. At times I noticed shooting phenomena from the outside, like smaller clouds suddenly moving across the surface of the disc.

Stimulus *V.*— The cloud suddenly came in from the outside, at about the same time as the after-image was noticed. It was very hazy at first, but slowly thickened to a very dense mist. The color did not seem to change in hue in any way, but the haze seemed to thicken and conceal it from view. The cloudy gray was somewhat darker than the background.

Stimulus *O.*— The after-image was seen very quickly, bordering the color almost all the way around; with this came a very peculiar cloud, which seemed to be a part of the after-image, extending over the color, hiding the color. For a while the view resembled the sun behind a luminous fog.

Stimulus *C*.— The color became almost a bright red behind the thin misty cloud, when the cloud would move a little to one side. The after-image and the cloud could be recognized as the same surface, floating over the surface as the eye moved. The cloud was smooth and not rough like the red. There were shooting phenomena as with the red.

Stimulus *G*.— The cloud appeared about the time the after-image was observed. When the haze became very thick, there was noticed a little yellow mixed with the misty surface. This was probably a hue-change of the stimulus-color. The cloud in the beginning seemed to move in from the outside, growing thicker towards the center.

Stimulus *GY*.— The cloud appeared as if in front of the stimulus-color in the form of a light hazy mist. It became thicker and thicker until the color was obscured. The color could be seen for a considerable time through the fog; as the mist grew thicker, the color appeared to lose in richness of chroma, until only a gray of about the same brightness as the background remained.

Observer Sh. Stimulus *Y*.— An after-image came very quickly, which extended all the way around the stimulus-disc. The after-image was at first very poor in chroma. Almost at the same time a whitish film began to form over the surface of the color. As it thickened, it appeared to be of the same brightness as the background. This gray surface began as a very thin sheet moving over the surface. At times it appeared as threads or filaments, stretching across the surface, as if they were in motion; these thickened into a solid uniform surface.

Stimulus *BG*.— There was a short interval of time before the after-image was seen on the border around the stimulus-color. The misty haze about the same time was observed to move inward over the surface of the color. The film soon thickened in texture so as to obscure the color.

Stimulus *B*.— The after-image began to show very quickly around the edge of the stimulus. The haze began to form almost as quickly, and thickened into a very white misty film. This stood out away from the color, and at no time did it appear to be a part of the stimulus-color. The color gradually lost in richness of chroma as the film thickened. When the cloud had taken on a filmy or sheet-like appearance, it was very easy to see that it was an extension of the after-image over the stimulus-color, as a misty white luminous fog. It looked very much like a thin sheet of tissue-paper spread over the color; the film at all times was in front of the color and not a part of the color. The whole adaptation-process for the blue was a fading out or disappearing of the color behind the fog.

Stimulus *R*.— The after-image appeared very quickly as a bluish-green border on one side of the disc. At first it was pale, or washed out. but it gradually increased in chroma until it was very rich. At the same time a haze began to form over the stimulus-color, which gradually grew thicker. The haze appeared to come from the outside of the disc and to settle in front of the color. This haze for the red was a rough, uneven mist or fog; not smooth in texture like that of the yellow or orange. The hue showed a remarkable change during the course of adaptation. It changed almost as soon as the haze began to form over the color into a red-orange, then to an orange of very poor chroma, and then to a very dirty, dingy brown. This brown was persistent for some time; finally it changed into a gray surface which was somewhat darker than the background.

Stimulus *V*.—A very pale, faded after-image soon appeared from

behind the stimulus-color, scarcely visible on the gray surface surrounding the stimulus. The cloud or fog seemed to float in from the side of the color towards the center; not so pronounced as with the red. The film at first was thin and more solid than with the red, but not so smooth in texture as with the blue or orange. (In three observations there was a slight hue-change towards blue, the red going out first. In two there was only a gradual fading out of the color into the fog).

Stimulus *O*.— The pale blue of the after-image, which was seen almost from the first, soon increased in chroma until it was a rich, well saturated blue. At the same time a beautiful hazy mist was gradually thickening over the color. This film appeared very much like the sun behind a thin fog. An interesting phenomenon occurred with a shift of the eye. There could always be observed two distinct discs in the visual field; the one was the stimulus-color, and the other was the film or fog in front of the color. These two discs, when not superimposed, the cloud upon the stimulus-color, always gave three parts of a circle. The part of the luminous fog which was upon the background showed a very rich after-image. The segment of the stimulus-color which was uncovered by the fog, caused by a shift of the eye, was a rich bright color, of the same hue as the stimulus-color; its brightness always depended upon the brightness-value of the background with reference to the brightness of the stimulus-color. The third portion was that part of the stimulus-color upon which a part of the cloud was superimposed. This was a beautiful gray, in which no color could be perceived in the final stage of adaptation.

Stimulus *C*.— The after-image was slow in appearing. The cloud effect was generally noticed as soon as the after-image. A change in brightness is always noticed as the filmy surface begins to form over the color. At this point the observer can always tell when adaptation is really progressing rapidly, because the color begins to pale out very rapidly. The luminous fog was always smooth, gradually thickening from a filmy surface to a veil very much like a thin sheet of paper spread over the surface of the color. This finally became so thick in texture that the color was obscured.

Stimulus *G*.— The cloudy mist began to form over the surface of the color by floating in from the outside towards the center of the disc. This movement and the after-image came at the same time. This haze grew thicker, which caused the color to become less and less saturated until only a gray surface was left. Generally there was a slight change in hue towards yellow.[17] The yellow would appear as if it were in the foggy veil which floated before the stimulus-color.

Stimulus *GY*.— The after-image began as a very pale, washed-out carmine. It extended all the way around the stimulus disc. With an increase in the richness of the chroma of the after-image also came a thickening of the hazy film which formed with the after-image. The cloud was apparently of the same brightness as the background. In nearly every case the green was observed to adapt out first, leaving a dirty, muddy surface which remained as a stubborn color for a considerable time.

Observer L. Stimulus *Y*.— Soon a film formed over the surface of the color, which did not appear uniform at first, but thicker in spots. The color began to lose in saturation from the first, changing its hue to a tan or very light unsaturated yellow. The haze finally grew so thick that the color was obscured from view.

[17] This was no doubt due to the fact that the Milton-Bradley *G* contains a slight amount of *Y*.

Stimulus *BG*.— The after-image and the cloud-effect appeared very quickly and at almost the same instant. The fog was very light and fluffy. It stood out in front of the color. The hue of the color gradually faded away behind this white mist as the fog became thicker. The final stage of adaptation gave a gray surface equal in brightness to the background.

Stimulus *B*.— The after-image was quickly observed; at about the same time the misty cloud spread quickly over the surface of the color. The fog was almost pure white and appeared to fit the stimulus-color. It seemed to stand out away from the color. This mist gradually thickened into a thick cloud which hid the color of the disc.

Stimulus *R*.— The cloud floated in over the surface of the color from the outer edge of the disc. It was not smooth in texture, but somewhat rough and uneven. The red disc changed at first into a kind of orange, then to a yellowish color of very poor chroma, and finally faded out to a dark gray.

Stimulus *V*.—.The after-image appeared very bright from the beginning. The misty haze is somewhat darker than the background. It gradually thickened over the color. It is difficult to tell the final gray, when adaptation is complete, from the violet when it is very poorly saturated.

Stimulus *O*.— The haze over the color and the after-image around the stimulus appeared at the same time. The cloud thickened and obscured the color from view. For some time the color could be seen as if shining through the fog. The final gray was of the same brightness as the background.

Stimulus *C*.— The after-image was at first dim and slow in appearing. The cloud was very thin at first and somewhat darker than the background. The color gradually paled away in the fog.

Stimulus *G*.— A very weak after-image appeared at first, which gradually increased in chroma. A misty cloud came in from the outside of the color towards the center. This haze increased in thickness until it obscured the stimulus-color. It is of the same brightness as the background.

Stimulus *GY*.— Cloud-effect appeared very quickly. This caused the color to become very much less saturated, as if a thin sheet of white paper had been suddenly spread over the surface. The mist thickened so as completely to hide the color. The final gray is the same as the background.

ADAPTATION TIMES IN SECONDS

AVERAGE OF FIVE OBSERVATIONS

Obs.	S		Sh		L		
Color	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av. of Av.
R	84.8	7.0	91.4	7.9	98.0	6.4	91.4
O	88.2	7.4	92.2	5.4	92.4	11.1	90.1
Y	97.6	5.9	90.8	3.8	98.8	7.4	95.7
YG	62.0	6.4	63.2	3.4	58.4	7.5	61.2
G	55.2	1.3	58.4	3.5	55.0	3.2	56.2
BG	42.0	5.2	39.8	4.2	39.2	3.0	40.3
B	125.0	7.2	107.2	12.6	128.4	4.9	120.2
V	82.4	2.4	84.0	3.2	78.0	5.6	81.3
C	73.2	6.2	73.4	7.3	75.4	6.9	74.0

The curve for the times of adaptation in sunlight differs considerably from the curve for the same colors at medium intensity. *R* is relatively shorter at medium intensity, while *B* is slightly longer than *B* in sunlight. On the other hand, the *Y* and *G* regions of the two curves take almost opposite positions. There is not only a rapid rise in the *Y* region for medium intensity, but there is a shift of the shortest time to the *BG* region. This difference might evidently be due to a difference in the chroma of the *Y* and *G* regions, caused by the two sources of illumination.[18] We therefore determined the chromatic limen of observer Sh for every color under both sources of illumination.

Procedure.—A color-mixer was placed in the window, on the table used in the preliminary experiment, so that the discs should revolve in a horizontal position. The disc was made up of a black-velvet paper, a good white, and a colored paper. The relative proportion of the brightness-value of the color was kept constant by varying the black and white discs as the color component was increased or decreased. The method of limits was employed (five series). *O* did not see the disc until it was in motion, and then only long enough to make a judgment. The experiment was repeated in the dark-room with the illumination used for medium intensity, and also in diffused daylight.

The *results* are shown in the following table:

CHROMATIC LIMENS

COLOR	SUNLIGHT		DARK ROOM ILLUMINATION		DIFFUSED DAYLIGHT	
	Av.	M.V.	Av.	M.V.	Av.	M.V.
R	18.0	3.6	22.0	6.4	19.3	1.6
O	34.0	3.8	20.0	6.2	8.0	1.3
Y	55.0	6.1	18.0	3.8	19.7	2.5
YG	46.0	4.3	28.0	5.2	23.0	3.6
G	37.0	4.3	32.0	4.3	22.2	2.3
BG	30.0	2.2	40.0	5.4	19.0	1.6
B	12.0	3.2	12.0	1.1	11.0	1.6
V	22.0	4.6	30.0	3.6	33.0	6.3
C	26.0	6.3	25.0	4.1	13.3	3.1

[18] The gray background upon which the stimulus-color was mounted, and which tested free from color under the daylight electric-bulb illumination, gave the following composition when placed in direct sunlight illumination: Black 215°, White 125°, B 12°, and G 8°.

There can be no doubt as to the effect of chroma on the time of adaptation in direct sunlight, and in illumination used in the dark-room experiment. The proportion, through the whole series of nine colors, runs in the right direction. Wherever the adaptation-time is long, the chromatic limen is small, and conversely. For diffused daylight, there is a slight variation; *R* and *V* are out of proportion. This exception may be due to the fact that *R* and *V* are the dark colors; since the illumination was rather weak, the limen would tend to be high. For all the lighter colors there is a close approximation to the law stated above, that where the time is high the limen is low. We shall later find that the same thing holds for spectral colors; chroma is the principal factor which influences the time of adaptation, with a possibility of intensity as a minor factor.

Part III.: Pure Spectral Colors

We proceed to describe the course of foveal adaptation to pure spectral colors, and to compare the behavior of these colors with that of surface-colors. We were careful to present the spectral color to *O* under controlled conditions. The wave-length of the spectral band producing the stimulus was determined before every observation; the intensity of the light producing the spectral color was always known; and the amount of light entering the eye was kept constant by the use of an artificial pupil.

Procedure.—The apparatus consisted of a remodeled spectrophotometer.[19] In addition to the original equipment of the apparatus, we inserted a field in front of the lens, so that any desired width of spectral band could be obtained in the form of a circular disc of color. An artificial pupil, 2.5 mm. in diameter, was placed 14 cm. in front of the stimulus field, and 2 mm. from the eye. A small projection-lantern, burning a 200 w. 115 v. Mazda nitrogen-filled daylight bulb, illuminated the spectroscope to produce the spectral colors. Before the lantern was placed a plate of thin and very finely ground glass to cut out the image of the filament in the light-bulb. The amount of light that entered the collimator of the spectroscope was 61.4 c. p.

The observations were made in the dark-room. All the light for illuminating the spectroscope was thoroughly concealed, so that only the color through the artificial pupil could be observed. A head-rest was set in front of the spectro-

[19] Manufactured by the Cambridge Scientific Instrument Co.

scope.[20] All changes in color-sensation were recorded in seconds by means of the apparatus described in Part II. *O* was given 15 min. of dark-adaptation before beginning the experimental work, and a period of 5 min. was allowed for rest between observations. Since monocular vision was employed, and the eyes were alternated from observation to observation, there was a period of at least 10 min. before an eye was restimulated.

For stimuli, circular fields were cut from the spectral band having the following wave-lengths; *R* 740-770 $\mu\mu$, *Y* 545-575 $\mu\mu$, *BG* 495-525 $\mu\mu$, *B* 440-470 $\mu\mu$, *V* 405-435 $\mu\mu$. The field was 6 mm. in diameter, and was just large enough to fall well within the macula lutea. The constancy of the light could be tested at any moment by means of a switch which turned the current through voltmeter and ammeter.

The *results* appear in the following table, as averages of five observations.

ADAPTATION TIMES IN SEC.

OBS.	SH.		S		Z		F		L		Av. of Av.
Color	Av.	Mv.	Av.	Mv.	Av.	Mv.	Av.	Mv.	Av.	Mv.	
R[21]	102	4	103	6	110	9	98	7	109	13	104.4
Y	166	10	164	10	180	21	Failed		166	7	169.0
BG	119	9	126	10	132	6	164	16	117	3	131.6
B	103	6	104	2	120	4	121	10	90	6	107.6
V	69	8	69	9	78	4	90	6	77	6	76.6

Observer F failed to get complete adaptation for *Y* at this intensity. In explanation we can only state that she had had less practice than the other *O*'s when she began the observations. All the others reported complete adaptation for all stimuli used.

The curve of the adaptation-times rises from *R*, reaches its maximum at *Y*, and gradually descends to *V*. This is almost an exact figure of the brightness-curve for spectral colors.[22]

[20] It was found at the beginning that any movement, even that of winking the eye, influenced the time of adaptation. The head-rest enabled the observer to hold the head in one position, leaving only steady fixation to be attended to. After a little practice with the artificial pupil, a good observer has no trouble in holding an observation period, often without even winking the eye.

[21] A psychological *R* was made up from gelatins. It was composed of *R* and *B* gelatins so combined that no hue-change was observed during the process of adaptation. The time of adaptation was: Sh 100, Mv. 3.2; S 104.2, Mv. 2.1; Z 104.9, Mv. 6.4; L 98.9, Mv. 11.2. F did not observe in this part of the series.

[22] W. de W. Abney, *Researches in Color Vision*, 78-111.

Hence we may have recourse to two factors, to explain the difference in the curves for surface-colors and for pure spectral colors: brightness and chroma. To test the first factor, we equated all the colors for brightness-value and then repeated the series, with the following result:

ADAPTATION TIMES IN SEC.

COLOR	SH.		S		L	
	Av.	Mv.	Av.	Mv.	Av.	Mv.
R	96	5.4	82	4.5	105	3.1
Y	115	6.6	120	3.0	130	6.9
BG	97	5.5	100	6.7	96	4.3
B	59	3.1	68	6.5	65	1.1
V	68	3.1	52	5.0	68	2.3

It is clear that an equation for brightness does not altogether remove our difficulty. To test the second factor, namely, the possible effect of chroma, we arranged a series of experiments as follows. Three color-fields were used: 4.5 mm., 3 mm., and 2 mm. in diameter. Since *V* has the lowest adaptation-time, a stimulus of this wave-length and brightness was set up on a second spectroscope. White light was added to another color in the spectrophotometer until the observer judged the two colors equal in chroma. When this point was reached, the observer was given 15 min. of dark-adaptation, and then observations were made with the three fields; the same colors were employed as in the first part of this experiment. The following are the averages for 10 observations by every observer on every field:

3MM. FIELD

OBS.	SH.		S		Z		F		L	
Color	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.	Av.	M.V.
R	47.2	5.4	63.4	3.3	48.0	6.0	62.4	4.8	67.0	9.2
Y	47.2	3.4	66.4	2.3	48.2	5.1	62.8	9.6	63.8	5.4
BG	47.2	2.6	65.2	7.4	46.0	4.4	60.5	3.1	74.2	4.8
B	41.8	1.8	57.8	5.4	45.6	3.4	61.9	3.1	70.0	2.8
V	44.4	2.4	63.0	4.4	46.2	4.2	62.6	8.2	67.8	3.4

4.5MM. FIELD

R	64.4	6.7	57.8	3.5	59.2	4.6	64.4	5.3	55.0	9.6
Y	46.0	4.4	75.8	5.0	46.0	4.0	50.2	1.9	74.2	6.5
BG	47.4	6.8	73.4	4.5	43.6	3.7	89.0	1.2	80.8	3.8
B	54.6	6.8	63.4	8.8	46.6	7.1	71.6	7.9	67.0	6.4
V	46.0	3.2	63.8	2.6	44.8	1.8	106.0	8.8	64.4	8.6

2MM. FIELD

R	50.6	5.7	62.0	4.8	46.2	3.8	55.1	6.3	64.2	10.6
Y	62.6	1.9	59.4	8.3	53.8	3.8	61.2	6.8	64.8	7.4
BG	47.8	7.0	56.6	10.0	50.6	5.9	70.0	10.2	65.0	5.2
B	52.8	9.8	69.2	3.0	55.0	4.4	51.1	7.1	63.8	5.6
V	57.0	2.0	58.6	8.5	53.4	4.7	52.4	6.4	67.2	14.1

The introspective reports may be summarized as follows:

Observer Z. *Y.*— After about 30 sec. I observed a thin filmy cloud which began to form on the rim of the circle. The cloud was darker than the *Y*, and contained some color. This film became thicker and darker until there was no color left. The *Y* under the film always became brighter, paler, and gradually took on a washed-out appearance.

R.— The red began to get lighter. The hue began soon to change to a very good orange. This began about the time a thin film was forming over the color. The filmy surface gradually grew darker and lost color, until a good gray surface covered the color. At the same time the hue changed from *O* to *Y*, and then finally to a gray.

G.— The green began to fade out to a *Y* as soon as it began to lose chroma. The loss of chroma began along the border of the colored field. I could recognize the after-image, when the eye moved, as being a portion of the filmy surface over the color. The film was a soft white cloud. The *Y* then faded out to a very good gray.

B.— The whole surface began to brighten up together with a reduction in chroma. There was no change in hue. The chroma gradually faded out to a good light gray. This process was like a cloud gradually thickening so as to obscure a color beneath it.

V.— The *V* began to lose chroma very quickly; at the same time there was a change in hue; first the red faded very quickly to a certain degree, then the blue, and finally both faded out together. This loss of chroma was again in the form of a white film collecting over the surface of the color. Began on the border of the field, and then spread to the center, all the time growing thicker until the color was obscured.

Observer S. *Y.*— There was no change in hue. In the beginning of observation there appeared a light ring around the edge of the stimulus-color due to contrast. The color gradually paled out to a good light gray surface.

R.— The red went immediately to a very pretty orange, and from this to a yellow. A dark gray cloud appeared in the center of the disc. This gradually spread out over the surface of the color, and covered the whole disc.

G.— There was no hue-change; only paled out to a good gray surface. The final stage was almost a white. The cloud first appeared in the center of the disc and spread over the whole surface of the stimulus-color.

B.— The blue did not change in hue, but lost in chroma, until a very pretty gray surface remained. The color gradually grew lighter as it lost in chroma. There appeared a gray cloud in the center of the disc which spread over the entire surface.

V.— The hue of the violet changed, first to blue, losing the red; then the bluish-violet lost in chroma, until a very dark gray surface remained. The cloud appeared in the center of the disc and spread over the surface of the color.

Observer Sh. *Y.*— A whitish film began immediately to collect over the surface of the stimulus-color. It appeared to be a little brighter than the color. The film gradually grew thicker until it obscured all the color, leaving only a light gray surface. There was no perceptible hue change.

R.—The red went through a color-change, first to orange, then through *O* to yellow, and finally to a dark gray. A film was observed forming over the surface of the color at the same time it began to change in color. The film began to form in the center of the stimulus-disc, and gradually spread outward, covering the whole disc.

G.— There was a change in brightness at the beginning. A bright ring was noticed around the edge of the field. This extended inward towards the center very quickly. Then a light film began to form over the surface of the color. This gradually grew thicker until all color was obscured. There was no hue-change.

B—There was a decided change in brightness. A light film formed immediately over the color. This grew thicker until all color was obscured. The resulting gray is almost a white.

V.— There was a change in hue towards the blue. The red faded out first; at the same time there was a loss in chroma, by a thin cloud forming over the surface. A very dark gray finally formed over the color.

Observer L. *Y.*—The color became a little lighter, and lost in chroma until it became a light gray. There was no hue-change.

R.— The *R* changed to *R-O, O, Y,* and finally to a dark gray.

G.— There was no hue-change. A cloudy mist began to form in the center of the circular field, and spread over the entire surface, which decreased the color in chroma until it was completely faded out.

B.— There was a gradual loss in chroma; no hue-change. A cloud-mist formed immediately over the surface of the color, which gradually thickened until no color was noticed. The final stage was almost white.

V.— There was a change in hue to a violet-blue color. The red almost faded out first; then the color was poor in chroma. The final stage was a very dark gray.

Observer F. *Y.*— The color grew paler by losing in chroma. There was no hue-change.

R.— There was decided hue-change in this color. It went to *O,* then to a very poor *YO,* which reminded me of a dirty *Y.* Finally lost in chroma, until a gray resulted which was darker than the color.

G.— The *G* lost in chroma by paling away. No hue-change.

B.—Same as the green.

V.—The *V* changed to *R* and then to *B,* all the time losing in chroma.

Since a chroma-match between two colors that differ in hue is only a relative matter, there will always be some variation. So far, therefore, as time of adaptation is concerned, we have every reason to be satisfied with our results. The averages for the 3 mm. field are, it is true, more uniform than those for the other two; the 4.5 mm. and the 2 mm. fields show slight fluctuations. But no variation is as great as with the brightness-equation.

From the introspective reports we find that there is no change in hue except for *R* and *V*. All the other colors which we used faded away steadily to a gray field. The adaptation-process makes its appearance in the form of a film or mist over the color. This causes the color to become less and less saturated, exactly as was the case with the surface colors. When there is a shift of the eye from fixation, *O* always reports three continuous portions of the field: a crescent of after-image; on the opposite side to this, a crescent of stimulus-color, very rich in chroma; and between the two crescents a white or gray surface over the stimulus-color.

ADAPTATION AT HIGH INTENSITY

It was found, in the first series with spectral colors, that foveal adaptation would not proceed to a neutral gray when the light that entered the collimator of the spectroscope was raised to more than 60 c. p. At the same time three important facts were observed in regard to foveal adaptation at high intensity. (1) All our records show that there is a tendency for eye-movement to increase very rapidly at the end of a fixation-period, in some cases as much as 4 or 5 times the amount at the beginning of a period. (2) Our *O*'s report that adaptation is always very rapid at the beginning of a period, no matter how high the intensity of illumination may be, provided it does not produce a blinding glare.[23] (3) There is always a good deal of pain in fixating a bright colored light, even with foveal fixation, when the intensity passes much beyond 100 c. p. This pain may be noticed even as long as two or three days after the observation. It appears, then, that when a certain intensity is reached the eye moves so frequently, during the latter part of the period, that the process of adaptation can not be completed. The pain is probably caused by the excessive contraction of the pupil in response to the reflex set up by the very intense beam of light striking the fovea through the artificial pupil. In the following experiment we tried to overcome these difficulties, and to study the process of adaptation at high intensities.

[23] See P. G. Nutting, *Trans. Illum. Eng. Soc.*, xi, 1916, 943.

Procedure.—The exposure-apparatus was a projection-lantern which burned a carbon 13 mm. in diameter, carrying a 30 amp. (125 v.) D. C. current. The lantern was mounted with a projection-lens of 2 in. diameter. In front of the projection-lens was placed a short-focus lens to bring all the rays of light to a pencil-focus. The actual amount of light focussed by the lens was about 6,200 c. p. The head of the observer was held in a steady position by means of a head-rest. The focus of light was adjusted to fall within the eye. Colored gelatin-filters (Eastman Kodak Co.) of known wave-length and transmission-power were used for stimuli; a filter of any desired color could be immediately fitted into one side of a pair of goggles, made to hold the filter securely. In the other side of the goggles was fitted a dark piece of card-board, to exclude all light from the unstimulated eye. A foveal comparison-light was set up in such manner that any spectral color, from the intensity afforded by the lantern to the lowest possible intensity, could be obtained immediately by shifting the lever of a rheostat. We measured the actual intensity of the light that entered the eye through the filters by the following method. A 500 watt Mazda lamp was screened to match daylight (acetylene flame and No. 79 filter) and was set up at one end of the photometer bench This procedure was adopted because the photometry of a carbon arc for this purpose is not as precise as the photometry of an incandescent lamp. A flicker photometer and a 20 c. p. comparison lamp were set up at the other end. When necessary, neutral-tint filters were used to reduce intensities.

For determining the transmission, a setting was made with the filter screening the 500 watt lamp, and then a setting was made without the filter; the ratio of these two readings on the candle-power scale gave the transmission. The following is an average of several trials:

COLOR	FILTER NO.	TRANSMISSION	x C.P. OF LANTERN=ABOUT	
R	70	7.6%	471.2	c.p.
Y	73	35.9%	2225.8	"
BG	75	18.6%	1153.2	"
B	48	19.5%	1209.0	"
V	76	1.6%	99.2	"

All work was done in the dark-room. *O* adjusted the filter to the eye, placed his head in the head-rest, and awaited the stimulus-light. The instructions were: "Fixate the bright circle of light until all color disappears. When you no longer see any color, remove the goggles, fixate the spectroscope, and describe what you observe." The following are the average adaptation-times in sec. for four observers:

R	Sh	92	The hue quickly changed to *O*, then to *Y*, very poor in chroma. The *Y* persisted for some time. Finally all hue disappeared. The foveal comparison-color was pure gray, much lighter than the stimulus-color. All intensities were gray.
	Z	109	
	S	120	
	F	100	
	Av.	105.3	
Y	Sh	165	There was no change in hue. The color gradually faded away. The comparison light at all intensities was almost white; no trace of color.
	Z	177	
	S	150	
	F	175	
	Av.	166.8	
BG	Sh	120	No change in hue. Very light gray. No color at any intensity.
	Z	112	
	S	98	
	F	130	
	Av.	120	
B	Sh	240	No change in hue. Very light gray for all intensities.
	Z	182	
	S	155	
	F	148	
	Av.	181.3	
V	Sh	200	There was a change in hue; the *R* apparently weakened first; then there was a noticeable decrease in chroma for the *B*. The *R* disappeared, leaving only a very weak unsaturated *B*, which slowly faded into a dark gray. The foveal comparison light showed no trace of color for any intensity.
	Z	183	
	S	185	
	F	220	
	Av.	197.0	

We were able to get complete foveal adaptation for all *O*'s with these intensities, as for all lower intensities. After a long fixation, beyond the point where adaptation was complete, we were able even to raise the comparison-light somewhat higher than the standard, and still had complete adaptation in the fovea. However, long fixation with a bright light is very painful; the pain even persists for two or three days as an ache or soreness within the eye.

It might be objected that the blinding glare of the positive after-image here influenced the judgment. We were, however, careful to test this factor before finally deciding upon the technique for the series. If the arc was fixated without the filter, there always resulted a blinding glare. When the foveal

comparison-light was fixated in this condition, there was only a slight change in brightness of the color, which immediately passed away. This was not true when a stimulus-color was fixated. The foveal comparison-light was always colorless, and so remained. It must, however, be small enough to fall within the foveal cup, and must not extend to the periphery of the macula.[24] Otherwise a more pronounced effect will be noted from glare.

Adaptation at high intensity is difficult to describe; but so far as we were able to observe the same general process takes place that has been observed throughout the earlier experiments of this study.

Conclusions

In general adaptation to direct sunlight, as well as under other conditions of adaptation, both to surface and to spectral colors, the fovea has a longer adaptation-time for color than any other part of the retina. This law aparently holds for high intensities as well as for medium and low intensities.

Chroma is the principal determinant of the rate of adaptation. Intensity is a second factor. The effect of both chroma and intensity has been observed with surface colors as well as with spectral colors.

The rate of adaptation is always faster at the beginning of a fixation-period, gradually decreasing, and becoming very slow at the end. The rate at the beginning also depends upon the chroma; the richer the chroma, the faster is the initial rate of adaptation. It gradually becomes slower later, and the whole process lasts longer than for a color poorer in chroma.

There is no difference in the experienced course of adaptation between a surface color and a pure spectral color. A color, under the process of adaptation, very quickly begins to decrease in chroma. This decrease is observed in the form of a light film which spreads over the color. The film continually thickens, until the color is obscured under the fog. The appearance of a color after adaptation corresponds in general to a mixture of that color with its complement. This relation was observed in nearly every observation. If the eye moved slightly from fixation, there were always reported three parts in the field: a crescent of the after-image, an opposed crescent of the stimulus-color, and an intermediate neutral gray surface.

Under suitable conditions, adaptation in direct vision can be carried to completeness at any physiological intensity.

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[24] J. von Kries, *Z. f. Psych. u. Phys. d. Sinnesorg.*, xv, 1897, 327.